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The infant Milky Way

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Abstract. We investigate the physical properties of the progenitors of today living Milky Way-like galaxies that are visible as Damped Lyα Absorption systems and Lyα Emitters at higher redshifts ($z \approx 2.3, 5.7$). To this aim we use a statistical merger-tree approach that follows the formation of the Galaxy and its dwarf satellites in a cosmological context, tracing the chemical evolution and stellar population history of the progenitor halos. The model accounts for the properties of the most metal-poor stars and local dwarf galaxies, providing insights on the early cosmic star-formation. Fruitful links between Galactic Archaeology and more distant galaxies are presented.

1. Background

One of the most popular methods to identify high-redshifts galaxies ($z \approx 2-7$) is by detecting their strong Lyα line. These Lyman Alpha Emitters (LAEs) are mainly associated to *star-forming galaxies*, and they have been extensively used to probe both the ionization state of the Inter Galactic Medium and the early galaxy evolution. At lower redshifts, $z < 5$, galaxies with *high neutral hydrogen column densities*, $N_{HI} > 10^{20.3}\text{cm}^{-2}$, can be identified in the spectra of more distant quasars by means of their strong Lyα absorption line. The most metal-poor among these Damped Lyα Absorption systems (DLAs), can provide insights on the initial metal-enrichment phases of galaxy formation. Recently a DLA with [Fe/H]≈ -3 observed at $z_{abs} \approx 2.3$, has indeed revealed strong carbon-enhancement and evident odd-even effect (Cooke et al. 2011b), consistent with the chemical imprint by $Z = 0$ faint supernovae (Kobayashi et al. 2011). Furthermore, all others DLAs with [Fe/H]< -2 observed at high-resolution show chemical abundance ratios consistent with those of very metal-poor Galactic halo stars (Cooke et al. 2011a), thus suggesting possible connections between these absorbers and the early building blocks of Milky Way (MW) -like galaxies. We determine the physical properties of the progenitors of the MW and its dwarf companions by using the merger-tree code GAMETE (GAlaxy MErger Tree & Evolution), which reconstructs the possible star-formation and chemical evolution histories of the MW system. The observed Lyα luminosity and Lyα line equivalent width are computed using the LAE model by Dayal and collaborators (Dayal et al. 2008, 2010) that reproduces a number of important observations for high-z LAEs. Adopting the canonical observational criteria we identify the progenitors visible as DLAs and LAEs at redshifts respectively equal to $z \approx 2.3$ and $z \approx 5.7$. The observable properties of the MW Galaxy and its neighboring companions are presented below, from present days back to the time when the Universe was only 1 Gyr old.

2. The Milky Way system at $z = 0$: Galactic Archaeology

Very metal-poor stars represent the living fossils of the first stellar generations. Their chemical abundance patterns and Metallicity Distribution Functions (MDFs) observed in both the stellar halo and in nearby dSph galaxies can provide fundamental insights on the properties of the first cosmic sources.

2.1. First stars and their Cosmic Relics

Cosmological simulations suggest that first stars formed at $z \approx 15-20$ in primordial H_2-cooling minihaloes and that were possibly more massive than typical stars forming today (Hosokawa et al. 2011). The transition from massive to normal stars is expected to be driven by metals *and* dust cooling, becoming important when the metallicity of the star-forming gas exceeds the critical value, $Z_{cr} = 10^{-4\pm1}Z_\odot$ (Schneider et al. 2002). We use our cosmological model to interpret the observed Galactic halo MDF. We find that the low-metallicity tail of the MDF strongly depends on the assumed Z_{cr} value (Fig. 1). If the observed cut-off (Schörck et al. 2009) suggests $Z_{cr} \approx 10^{-4}Z_\odot$, the presence of the four stars at [Fe/H]< -4.5 can only be accounted if $Z_{cr} < 10^{-5}Z_\odot$. In particular, the existence of the most metal-deficient star ever, which has *total* metallicity $Z \approx 10^{-4.5}Z_\odot$ (Caffau et al. 2011) clearly requires $Z_{cr} < 10^{-4}Z_\odot$. Such a recent discovery definitely proves that dust strongly governs the transition from massive to normal stars in the low-Z regimes (Schneider et al. 2002).

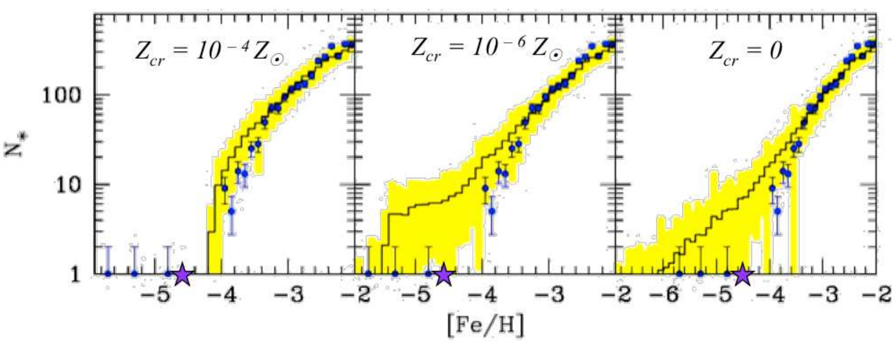

Figure 1. The Galactic halo MDF: observations (points (Beers & Christlieb 2005)) vs simulations averaged over 100 possible MW merger histories (histograms and shaded area). The starred symbol indicates the most metal-deficient star.

The chemical abundance patterns of halo stars with $-4.5 <$[Fe/H]< -2.7 (Cayrel et al. 2004; Caffau et al. 2011), do not show any peculiar imprint from very massive primordial stars, and have small chemical abundance scatter unlikely resulting from individual supernovae (SN) ejecta. According to our cosmological model (Salvadori et al. 2007) the number of stars formed out of gas polluted *only* by $Z < Z_{cr}$ stars is extremely small, and thus negligible in current data sample. These "second-generation" stars can either have low or high [Fe/H] (Fig. 2) if they form in halos that accreted metal-enriched gas from the MW environment or that are self-enriched by the first stars. To have the chance to detect the chemical imprint by first stars an higher number of [Fe/H]< -2 stars is clearly needed. To this aim it is useful to survey the stellar halo between 20 kpc $\lesssim r \lesssim$ 40 kpc, where the contribution of [Fe/H]< -2 stars with respect to the overall stellar population is expected to be maximal (Salvadori et al. 2010b).

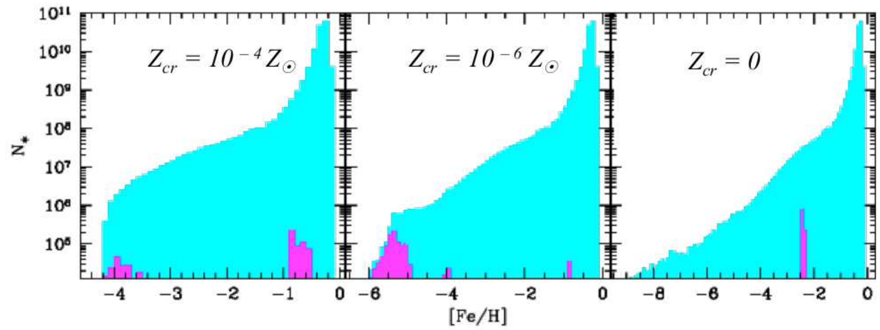

Figure 2. Number of stars predicted to exist at $z = 0$ as a function of their [Fe/H] for different Z_{cr} models. The magenta histograms show second-generation stars, the cyan histograms the overall stellar populations.

2.2. First Galaxies and their Cosmic Relics

An alternative way to find very metal-poor stars is by surveying dSph galaxies and in particular ultra-faint dSphs ($L < 10^5 L_{\odot}$, Fig. 2), in which [Fe/H]< -3 stars represent the 25% of the total stellar mass. These faint dwarfs are predicted to be among the first star-forming galaxies in the MW system, left-overs of H_2-cooling minihaloes formed at $z > 8.5$ (Salvadori & Ferrara 2009), i.e. before the end of reionization ($z_{rei} = 6$). In these galaxies the higher fraction of [Fe/H]< -3 stars with respect to the more luminous "classical dSphs" reflects both the lower star-formation rate, caused by ineffective H_2 cooling, and the lower metal (pre-)enrichment of the MW-environment at their further formation epoch. Indeed classical dSphs are find to finally assemble at $z < 7$ when the pre-enrichment of the MW environment was [Fe/H]≈ -3. The few stars at [Fe/H]< -3 observed in classical dSphs (Starkenburg et al. 2010) are predicted to form in progenitor minihaloes at $z > 8.5$ (Salvadori & Ferrara 2009), some of which might host first stars. The unusual composition of two stars at [Fe/H]≈ -2 observed in Hercules (Koch et al. 2008) might be the result of self-enrichment by first stars in early progenitor halos.

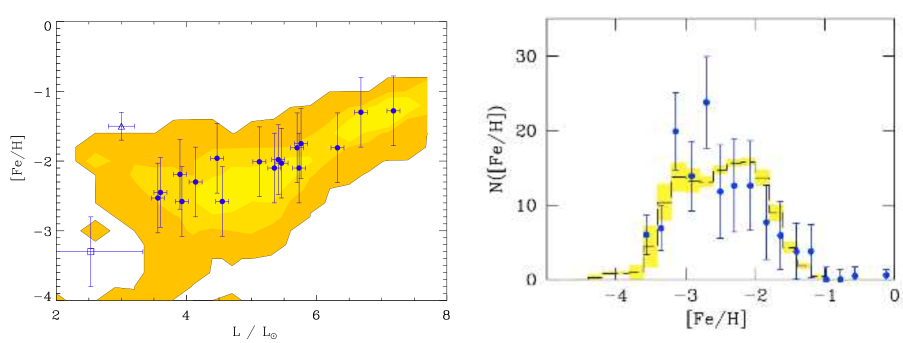

Figure 3. Observed (points with error-bars, (Kirby et al. 2008)) vs simulated (contours/histograms) properties of dSph galaxies at $z = 0$. *Left:* the iron-luminosity relation. The colored shaded areas correspond to regions including the (99, 95, 68)% of the total number of dSph candidates in 50 MW merger histories (Salvadori & Ferrara 2012). *Right:* MDF of ultra-faint dSph galaxies (Salvadori & Ferrara 2009).

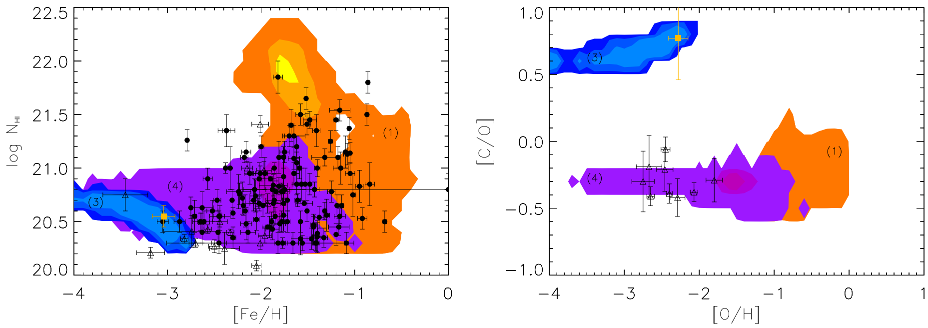

Figure 4. MW progenitors visible as DLAs at $z \approx 2.3$ (contours), with color intensity corresponding to regions containing the (99, 95, 68)% of DLAs in 50 merger histories (Salvadori & Ferrara 2012). Points with error-bars are observations: circles (Prochaska et al. 2007), triangles (Cooke et al. 2011a), square (Cooke et al. 2011b).

3. The Milky Way system at $z \approx 2.3$: DLAs

The predicted N_{HI} vs [Fe/H] values of the MW progenitors visible as DLAs at $z \approx 2.3$ follows the observed relation (Fig. 4). In our picture very metal-poor DLAs, [Fe/H]<-2, are associated to starless $M \approx 10^8 M_\odot$ minihaloes that virialize from metal-enriched regions of the MW environment before the end of reionization and passively evolve down to $z \approx 2.3$. These sterile absorbers retain the chemical imprint of the dominant stellar populations that pollute the MW environment at their formation epoch: low-Z SN type II (Salvadori et al. 2007). This finding agrees with the observational results by Becker et al. (2012) that show that the gas chemical abundance ratios in very metal-poor DLAs/sub-DLAs do not significantly evolve between $2 < z < 5$. The recently discovered C-enhanced DLA is instead pertaining to a new class of absorbers hosting first stars along with second-generation of long-living low-mass stars. These peculiar DLAs are descendants of $M \approx 10^7 M_\odot$ minihaloes, that virialize at $z > 8$ in neutral primordial regions of the MW environment and passively evolve after a short *initial period of star formation*. These conditions are only satisfied by $\approx 0.01\%$ of the total amount of DLAs, making these absorbers extremely rare. The peculiar abundance pattern observed in the C-enhanced DLA results from the enrichment by low-metallicity SN typeII and AGB stars, which may start to form as soon as $Z > Z_{cr}$. While SNII nucleosynthetic products are mostly lost in winds, AGB metals are retained in the ISM, causing a dramatic increase of [C/Fe]. The amount of N produced by $Z < 5 \times 10^{-4} Z_\odot$ AGB stars is very limited (Meynet & Maeder 2002), resulting in a gas abundance [N/H]$= -3.8 \pm 0.9$ (see Fig. 5). The mass of relic stars in C-enhanced DLAs is $M_* \approx 10^{2-4} M_\odot$, making them the gas-rich counterpart of the faintest dwarfs.

4. The Milky Way system at $z \approx 5.7$: LAEs

At $z \approx 5.7$ the star-forming progenitors of MW-like galaxies cover a wide range of observed Lyα luminosity, $L_\alpha = 10^{39-43.25}$ erg s^{-1}. The probability to have at least one progenitor observable as LAE ($L_\alpha \geq 10^{42}$, $EW \geq 20$ Å) is therefore very high $P \geq 68\%$. Such visible progenitors are mainly associated with the most massive halos of the hierarchy, i.e. the major branch, with total mass $M > 10^{9.5} M_\odot$. On average

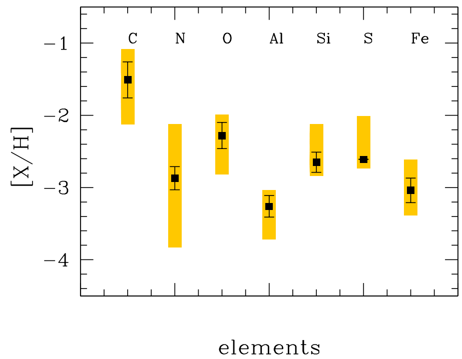

Figure 5. Gas chemical abundances in the C-enhanced DLA: observations (points, Cooke et al. (2011a)) vs simulations (average value $\pm 1\sigma$, shaded areas).

the identified LAEs have star-formation rates $\dot{M}_* \approx 2.3 M_\odot$/yr and $L_\alpha \approx 10^{42.2}$erg/s. They are populated by intermediate age stars, $t_* \approx 150 - 400$ Myr, which have average metallicities $Z \approx (0.3–1) Z_\odot$ (Fig.6). Interestingly these visible MW progenitors provide more than the 10% of the very metal-poor stars that are observed today in the Galactic halo. Indeed, most of these [Fe/H]< -2 stars formed at $z > 6$ in newly virializing halos, accreting metal-enriched gas from the MW environment. By $z \approx 5.7$ many of these premature building blocks have already merged into the major branch of the hierarchy, i.e. the visible progenitor (Salvadori et al. 2010a).

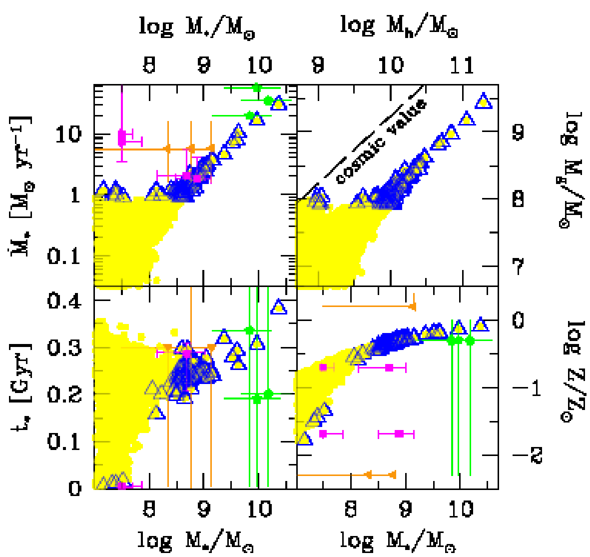

Figure 6. Physical properties of MW progenitors (yellow circles) at $z \approx 5.7$. Blue triangles identify the objects visible as LAEs. Points with error-bars are data by Ono et al. (2010) (magenta squares, 4 models for 1 LAE), Pirzkal et al. (2007) (blue triangles) and Lai et al. (2007) (green circles). As a function of the total stellar mass the panels show: the instantaneous star formation rate (a), the average stellar age (c) and (d) metallicity (d). Panel (b) shows the relation between the halo and the gas mass, with the cosmic value pointed out by the dashed line.

5. Conclusions

The MW system is a powerful laboratory to study early galaxy formation. On the one hand the properties of the first cosmic sources can be studied by exploiting the observations of today living metal-poor stars and galaxies. From the other hand the early evolutionary stages of different MW progenitors can be investigated using complementary observations of high-z galaxies. In particular, by identifying the MW progenitors among the faintest LAEs observed at $z \approx 5.7$ it will be possible to observe the MW in its infancy, when it was only 1 Gyr old.

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